

The Estimation of Atmospheric Electrical Path Length by Passive Microwave
Radiometry¹

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Abstract - A technique is described for using microwave radiometric measurements to estimate variations in atmospheric electrical path length. Results of numerical experiments indicate that the zenith electrical path length can be inferred with an accuracy of 1 or 2 cm by using this technique.

One problem encountered in any experiment requiring coherent reception of radio waves at separated stations is the determination of the electrical path length changes caused by the atmosphere. For example, in radio astronomy such a problem arises when long-baseline interferometers are used to observe small radio sources, and phase preservation is desired. From ground-level measurements of temperature, pressure, and relative humidity at each of the receiving stations, the variations in atmospheric electrical path length can be estimated. A more accurate method for inferring these path-length variations incorporates measurements by passive microwave radiometers of atmospheric thermal emission near the 22.235 GHz resonance line of water vapor and the 60 GHz resonance band of oxygen. The radiometers would have narrow-beam antennas pointed along each ray path for which the atmospheric path length is to be estimated. The electrical path length increase can be estimated from the radiometric measurements and the surface meteorological quantities as described below.

The increase in electrical path length caused by the atmosphere is

$$\Delta L = \int_L (n-1) \, d\ell ,$$

(1)

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where n is the index of refraction, and L is the path of the electrical signal. The index of refraction of the atmosphere may be related to meteorological quantities. For frequencies below approximately 30 GHz, the relation is²

$$(n-1) = \frac{7.76 \times 10^{-5}}{T} (P + 4.8 \times 10^3 \frac{e}{T}), \quad (2)$$

where T is temperature ($^{\circ}\text{K}$), P is total pressure (mb), and e is partial pressure of water vapor (mb).

The variability in the electrical path length is dominated by the variability in water vapor content of the atmosphere, although the average value is determined mainly by the dry-air contribution. Because surface humidity is not well correlated with humidity at higher altitudes and ΔL is given by an integral over the radio signal path, surface measurements of meteorological quantities do not permit an accurate estimate. The sky-brightness temperature near 1-cm wavelength, however, is more highly correlated with atmospheric path length. The brightness temperature depends upon meteorological conditions along the propagation path and may be determined theoretically by integration of the radiative transfer equation.³

$$T_B(\nu) = \int_L T(\ell) \cdot \left[\exp \left\{ - \int_0^{\ell} k_{\nu}(\ell') d\ell' \right\} \right] k_{\nu}(\ell) d\ell, \quad (3)$$

where $T_B(\nu)$ is brightness temperature at frequency ν , $T(\ell)$ is atmospheric temperature at position ℓ on path L , and $k_{\nu}(\ell)$ is the atmospheric absorption coefficient at frequency ν and position ℓ on path L .

In principle, Eq. (3) may be inverted to yield meteorological information from measurements of microwave brightness temperature. The data-inversion technique used here for inferring atmospheric electrical path length from microwave brightness temperature measurements is essentially a multidimensional regression analysis. The estimate of the atmospheric component of the electrical path length, ΔL^* , is expressed as a linear combination of the

various data elements d_i

$$\Delta L^* = \sum_i D_i d_i. \quad (4)$$

The constants D_i are determined by minimizing the expected mean-square difference between the estimate ΔL^* and the true value ΔL , and are given by

$$D_i = \sum_j \overline{[\Delta L \cdot d_j]} \cdot \overline{[d_j \cdot d_i]}^{-1}, \quad (5)$$

where $\overline{[]}$ denotes expected value, and $\overline{[d_j \cdot d_i]}^{-1}$ is the j - i th element of the inverse of the matrix $\overline{[d_j \cdot d_i]}$.

For our numerical experiments, atmospheric statistics were obtained from 50 summer and 50 winter United States Weather Bureau radiosonde records from Huntington, West Virginia. The summer records were taken over a 5-year period (1962-1966) at 12-hour intervals for the first 5 days in August, and the winter records for the same period in February. Using Eqs. (1) and (2), we calculated the atmospheric path length increase for each of the radiosonde records for various elevations angles. Brightness temperatures were calculated by using Eq. (3) and the absorption coefficients for water vapor and oxygen as expressed by Staelin⁴ and Barrett, et al.⁵, respectively. Refractive bending attributable to the atmosphere was included in the calculations, but effects of clouds were not. The constants D_i were then computed from Eq. (5), by using as data elements the ensemble of surface meteorological quantities and computed brightness temperatures. A constant of unity was also used as a data element to bias the estimate of ΔL toward its mean value. Next, Gaussian noise of rms value:

2% for surface relative humidity

0.1°K for surface temperature

1 mb for surface pressure

0.2°K for brightness temperatures

was added to the simulated data, and ΔL^* calculated from Eq. (4). The inferred value, ΔL^* , was then compared with the computed true value, ΔL , for each of the 100 radisonde records, and the rms error in ΔL^* was determined.

Results of the numerical experiments are shown in Table 1 for summer and winter cases. The rms error in the estimated value of the zenith electrical path length is given for 3 estimation schemes using: (i) surface meteorological data alone; (ii) surface meteorological data plus brightness temperatures at two frequencies near the 22.2 GHz water vapor resonance; and (iii) surface meteorological data plus brightness temperatures at two frequencies near the 22.2 GHz water-vapor resonance and at two frequencies near the 60 GHz oxygen band. The water-vapor information is principally responsible for the indicated improvement, and the oxygen measurements refine the results by providing information about the atmospheric temperature profile. The calculations show that approximate rms errors for non-zenith directions can be obtained by multiplying the appropriate entries in Table 1 by the secant of the zenith angle, for zenith angles less than 80°.

The results of these calculations indicate that in the absence of clouds the atmospheric contribution to the zenith electrical path length can be inferred with an accuracy of 1 or 2 cm from measurements of sky brightness temperature at 2 frequencies near the water-vapor resonance, and surface measurements of meteorological quantities. Better accuracy can be obtained by including microwave radiometric measurements near the O₂ band. For summer, this is approximately a factor of 3 better than could be done from a priori statistical information alone and a factor of 2.5 better than could be obtained by measuring only surface meteorological quantities. Preliminary calculations indicate that typical clouds will add approximately 0.5 cm to

the expected rms error in inferring zenith electrical path length increase from multifrequency radiometric data.

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TABLE 1. Results of estimating atmospheric zenith electrical path length.

Measurements for the estimation of path length	RMS errors in estimated path length (cm)	
	Summer	Winter
A priori standard deviation in zenith electrical path (no measurements)	4.4	2.2
Surface meteorological data: temperature, pressure, relative humidity	3.7	2.0
Surface meteorological data plus brightness temperatures at 22 and 24 GHz	1.4	1.0
Surface meteorological data plus brightness temperatures at 22, 24, 52.65, 53.60 GHz	1.1	0.8

References

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